8.2 THE ROLE OF MULTI-LAKE INTERACTIONS IN THE MODULATION OF LAKE-EFFECT SNOWSTORMS

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1. INTRODUCTION

Lake-effect snowstorms (LESs) frequently produce hazardous winter weather conditions in the Great Lakes region, placing the local residents at risk. Moreover, the economic burden resulting from the heavy snowfall, placed on commerce and municipalities, can be substantial (Schmidlin 1993). To minimize the risk and burden, more adequate preparation for these events must be completed. However, the preparation can only be effective if these events are predicted to a high degree of accuracy and precision. Improvement in the operational prediction process, as mesoscale numerical weather prediction models become a foundational tool, must be achieved through interpretation of model output based upon knowledge of the dynamics of the collective Great Lakes system.

Some preliminary studies have shown that multi-lake influences may be an important aspect of the LES precipitation distribution. Byrd et al. (1995) illustrated that the presence of Lake Huron modified significantly the LES patterns near Lake Ontario. Sousounis and Mann (1999) showed that the formation of a collective lake disturbance (CoLD) can influence the LES environment and precipitation. The relative importance of these two effects (i.e., upstream lakes and collective effects) is not known. For example, the LES modifications attributed to a developing CoLD may simply be a result of the presence of an upstream lake. However, if these two influences are different, then several upstream lakes or even "downstream" lakes may have an effect on LES evolution.

Several high resolution (e.g., nested 6.67 km grids) numerical simulations were performed for a particular event in December 1996 with the PSU/NCAR mesoscale model MM5 (Grell et al. 1995) to examine multi-lake processes as they relate to Lake Michigan LES events. Simulations including all of the Great Lakes (WL), only Lake Superior and Lake Michigan (LMLS), only Lake Michigan (LM), only Lake Superior (LS) and none of the lakes (NL) were done. Comparisons among simulation results were used to isolate and evaluate the contributions from the various lakes.

2. SIMULATION COMPARISON

Simulations of a significant lake-effect and CoLD event that occurred December 18-20, 1996 are used to demonstrate the multi-lake effects on LESs. Intercomparison of the simulation results reveals differences in location, duration, intensity, and even morphology among the individual lake (LM), the adjacent upstream lake (LMLS), and the aggregate (WL) outcomes. Figure 1 illustrates these differences in areal averaged hourly precipitation downwind of southern Lake Michigan. The lack of significant NL precipitation indicates that the totals were primarily a result of LES activity. One key finding is that the timing of the precipitation maxima was delayed when other lakes were present in the system. Additionally, the

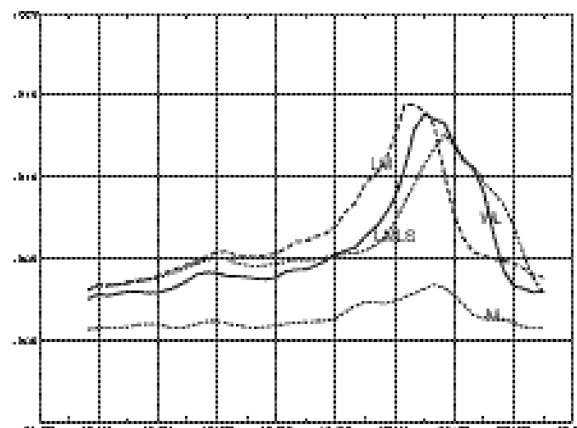

FIG. 1. Time series comparison of precipitation downwind of southern Lake Michigan averaged over area in Fig. 3 from the WL, NL, LM, and LMLS simulations. Values are in inches.

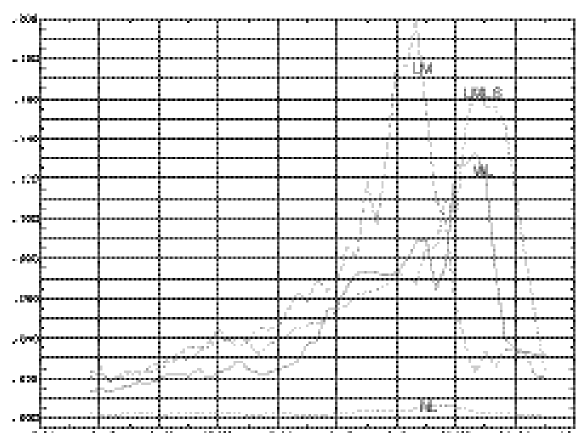

FIG 2. Time series of localized maxima in precipitation downwind of Lake Michigan (area in Fig. 3) for WL, NL, LM, and LMLS simulations. Values are in inches.

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TABLE 1. Simulation comparison of maximum convective available potential energy (CAPE) and the maximum one hour precipitation for the WL and LMLS simulations.

Simulation	CAPE	Max 1h Precip
WL	78 J kg^{-1}	0.33 cm
LMLS	148 J kg^{-1}	0.43 cm

inclusion of both upstream and downstream lakes reduced the overall areal intensity of the precipitation. The localized point maxima in hourly precipitation were also reduced (Fig. 2). Thus, the downstream lakes (Huron, Erie, and Ontario) reduced the overall intensity of LESs near Lake Michigan. The reduction in intensity was a result of increased warming by the developing aggregate disturbance near the top of the convective boundary layer (not shown), which stabilized that layer and reduced the overall convective potential (Table 1).

Morphology (Hjelmfelt 1990) refers to the different types of observable characteristics of the lake-effect convective structures, primarily from a satellite perspective. The morphology of LESs includes mid-lake bands, shore-parallel bands, mesoscale vortices, and multiple wind parallel bands. Additionally, "dominant" band structures have been observed under conditions favorable for the formation of multiple wind parallel bands (Wagenmaker and Smith 1995). Because of their intensity and size, these dominant band events could also be considered a morphological category. It was originally proposed that geographical influences (e.g., upwind bays or peninsulas) were important in the development of these dominant bands (Wagenmaker and Smith 1995). However, Figure 3 shows a disperse precipitation signature in the LM simulation, which is characteristic of wind parallel bands; and a concentrated precipitation signature in the WL simulation, which is characteristic of a dominant, wind parallel band; and hence suggests the importance of aggregate forcing.

In this event, the formation of a dominant band in the WL simulation can be attributed mainly to the interactions between the local lake (e.g., Lake Michigan) and the adjacent upstream lake (e.g., Lake Superior). Moreover, the presence of the downstream lakes (e.g., Lakes Huron, Erie, and Ontario) subsequently modified the duration and intensity of the dominant band, which is evident in the previous time series plots (compare WL and LMLS results). This modification was a further manifestation of multiple lake-lake(s) interactions.

Stein and Alpert (1993) presented an effective technique for evaluating quantitatively the contributions of different physical processes within a particular system through designing and analyzing an appropriate suite of numerical sensitivity experiments. An important aspect is that synergistic interactions amongst the contributors can be isolated. For instance, the direct contribution from Lake Michigan on LESs is determined by removing the background (synoptic-scale) signal, which is contained in the NL simulation, from the simulation that includes only Lake Michigan (e.g., LM' = LM - NL). Note that the LM' term contains the synergistic contributions between the background and Lake Michigan, which cannot be removed. In the same manner, the synergistic terms related to interactions between Lakes

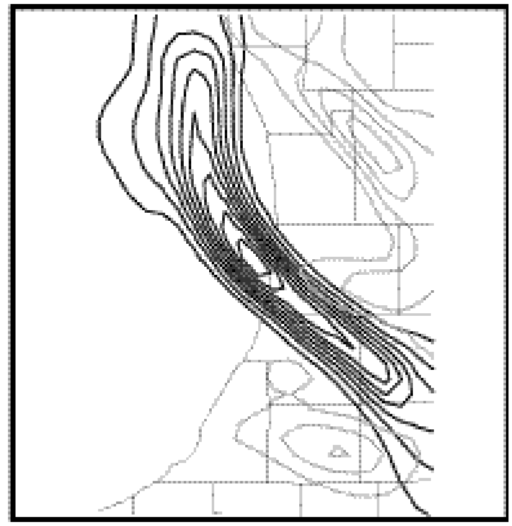

FIG. 3. Hourly precipitation near southern Lake Michigan for WL (dark) and LM (light) simulations valid at 03 UTC 20 December 1996 illustrating the morphological differences.

Michigan and Superior can be isolated by the following manipulation:

$$I_{LMLS}=(LMLS-NL)-[(LM-NL)+(LS-NL)]=LMLS'-(LM'+LS').$$

Likewise, the synergistic terms associated with interactions between Lake Michigan and the downwind (Eastern) lakes (EL) can be isolated using:

$$I_{LMEL}=(LMEL-NL)-[(LM-NL)+(EL-NL)]=LMEL'-(LM'+EL').$$

It should be noted that the I_{LMLS} term contains many non-linear interactions that involve Lake Michigan and Lake Superior, which cannot be individually isolated. Likewise, the I_{LMEL} term contains interactions that involve Lake Michigan and the eastern lakes, which cannot be individually isolated. Figure 4 demonstrates the relative contributions from these various terms on lake-effect precipitation near southern Lake Michigan. Notice that the primary contributor to the precipitation throughout the first portion of the event was Lake Michigan (compare Tot and LM'). However, as the regional scale disturbance matured, the synergistic terms associated with interactions among the lakes became increasingly important as well. The overall effect of interactions with the downstream lakes was to reduce the precipitation (negative I_{LMEL} term). This effect was also true for the interaction with the upstream lake until near the end of the period (I_{LMLS} term). Analyses show that these reductions were a result of modification to the thermodynamic profile that translated into a reduction of convective potential. Late in the event, the processes that involve both Lake Michigan and Lake Superior generated a significant increase in precipitation. This indicates that the dominant band formation may have been a result of processes related to pre-conditioning of the lower troposphere by Lake Superior in this case. The pre-conditioning also appears to be dynamic as opposed to thermodynamic. That is, the wind field

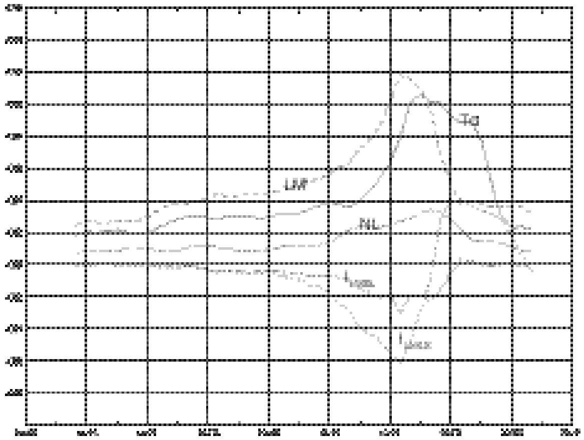

FIG. 4. Time series of contributions to hourly precipitation near southern Lake Michigan (area in Fig. 3). Curves represent factored elements attributed to the total Great Lakes perturbation (Tot) (i.e., WL-NL), the background (NL), Lake Michigan (LM'), interactions between lakes Michigan and Superior (I_{LMLS}), and interactions between Lake Michigan and the downstream lakes (I_{LMEL}). Values are in inches.

became more favorable for the development of the dominant band.

Specifically, the mechanisms responsible for the development of the dominant band seem to be related to the maturation of a localized low-level jetlet. Recently, a single diabatic heat source has been linked to the formation of mid-tropospheric jetlets in mesoscale convective systems (Hamilton et al. 1998). The jetlet forms as a result of adjacent positive and negative height perturbations. In general, if these perturbations are in phase with the ambient flow (e.g., negative height perturbation to the left of the mean flow vector), then the height gradient is locally increased. A mesoscale jetlet eventually forms between the perturbations through geostrophic adjustment to the imposed imbalance. The jetlet forces transverse ageostrophic circulations (Uccellini and Johnson 1979), which when superimposed on a convectively unstable boundary layer, organize convective motions in the favored regions of jetlet induced ascent. The formation of the jetlet in this event was correlated with a coupling of two diabatic heat-induced perturbations that occurred at different levels (e.g., elevated heating adjacent to shallow heating). The net result was a localized positive height perturbation that was adjacent to a localized negative height perturbation (Fig. 5) with the jetlet located between them. The dominant band developed in the region of the jetlet.

3. CONCEPTUAL DEVELOPMENT

Conceptually, the Great Lakes force and modulate LESs in the vicinity of Lake Michigan on three organizational scales: "local/individual", "adjacent" and "collective" lake scales. On the local lake organizational scale, strong convective heat and moisture fluxes from Lake Michigan modify the boundary layer, resulting in LES formation. On the adjacent lake organizational scale, the ambient flow advects the local influences from Lake Superior downstream, which modify the

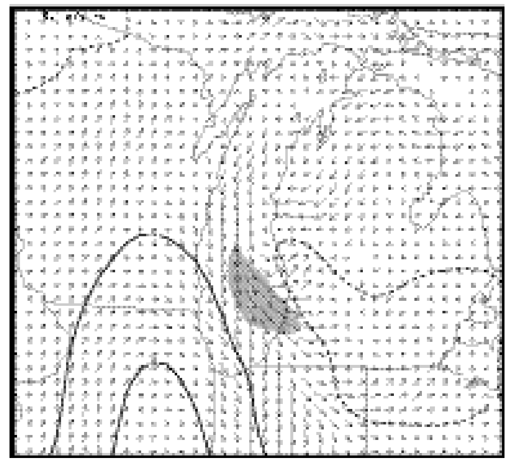

FIG 5. 750 hPa WL-LM perturbations of height (contour interval 4m, negative dashed), wind speed (shaded regions > 8 m s^{-1}), and wind (vectors- reference vector in upper left corner) illustrating the maturation of a jetlet at 00 UTC 20 December 1996.

thermodynamic and dynamic structures of the convective boundary layer over Lake Michigan. This modification to the LES environment accomplishes the same result that synoptic-scale modification (Niziol 1987) has on adjustment to LES evolution (e.g., location, duration, intensity and morphology). On the collective lake organizational scale, interactions among all the lakes generate a larger meso-α scale response, which leads to further thermodynamic and dynamic modification over Lake Michigan and further LES modulation. These processes occur both sequentially and simultaneously as the event progresses (i.e. individual lake forcing does not end when interactions with other lakes begin). In addition, the interactions tend to offset the direct contributions made by the individual and adjacent lakes. However, in localized regions, significant enhancement of LESs can occur as a result of strong mesoscale dynamical forcing (e.g., the formation of a mesoscale jetlet) indicating that the development of dominant band structures requires some degree of lower tropospheric pre-conditioning. To summarize, the development of a regional scale disturbance can have a significant influence on the evolution of LESs. Additionally, the modulation of LESs in such events is not purely a result of adjacent upstream lake modification. Multi-lake non-linear/ synergistic processes are also important for altering LES evolution.

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